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ADS-B used in Improvement of Air Traffic Control

Hao Wang
Purdue University

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Dengfeng Sun
Chair

Haifeng Wang

Nan Kong

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Approved by: William Anderson 4/15/2015
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LIST OF ABBREVIATIONS

ADS-B	Automatic dependent surveillance – broadcast
SSR	Secondary surveillance radar
MSSR	Monopulse secondary surveillance radar
PSR	Primary surveillance radar
UAT	Universal access transceiver
FAA	Federal Aviation Administration
IGS	International GNSS Service
GNSS	Global navigation satellite system
ATC	Air traffic control
NAS	National airspace system
DOP	Dilution of precision
ATCSCC	Air Traffic Control System Command Center
ARTCC	Air Route Traffic Control Center
TRACON	Terminal Radar Approach Control
ATCRBS	Air Traffic Control Radar Beacon System
TCAS	Traffic Collision Avoidance System
RE	Range error

URE	User range error
CS	Control Segment
RNM	Noise and multipath
WGS	World Geodetic System

ABSTRACT

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Automatic dependent surveillance – broadcast (ADS–B) is a central component of the NextGen air traffic control program. This surveillance technology can replace current secondary surveillance radars (SSR) and improve cockpit situational awareness. The service can improve traffic surveillance capabilities by sharing accurate aircraft position information between pilots and air traffic controllers. In addition, ADS-B provides pilots with weather as well as air traffic information for nearby area. In order to receive these traffic and weather services, a pilot must have appropriate onboard equipment including GPS receiver, Universal Access Transceiver, antenna and multi-function cockpit display which is capable of receiving and displaying information. Compared to traditional surveillance technology used in air traffic control, aircraft updates and broadcasts its information more rapidly with ADS-B since it determines its position via satellite navigation, enabling it to be tracked. ADS-B also has a large coverage including most of areas in the world. This feature is especially helpful in special areas such as mountain area for air traffic controllers. The most important potential of ADS-B is to enable procedures not possible with current SSR that would increase the capacity of airspace system due to its high navigation accuracy. ADS-B is also helpful to improve the safety in air traffic. However, ADS-B program hasn’t been operating well even though FAA highly recommended it and made rules on it. This paper discussed the basic advantages and disadvantages of ADS-B. The experiment was designed to estimate the navigation accuracy of ADS-B by modeling several flights in MATLAB with data from FAA and IGS and then compare the result in ideal situation with current surveillance technology. The result showed that the accuracy of ADS-B is higher than current radar system in this designed situation. The limit of the experiment and its difference to the real world are discussed in the paper as well.

CHAPTER 1. INTRODUCTION AND MOTIVATION

Automatic dependent surveillance – broadcast (ADS–B) is a technology that could fundamentally change the way of tracking aircraft in airspace. This is a cornerstone of NextGen air traffic modernization program. It is a cooperative surveillance technology in which an aircraft determines its position via GNSS and broadcasts it, making it possible to be tracked. The information can be received by air traffic control ground stations and other aircraft. As a result, ADS-B is treated as a replacement for traditional secondary radar. Its signals can also be received by other aircraft nearby to provide situational awareness and allow self-separation. ADS-B is expected to be the basis of the future surveillance system in the United States.

As shown on FAA official website, the coverage of ADS-B service in United States is almost the whole map of the U.S.

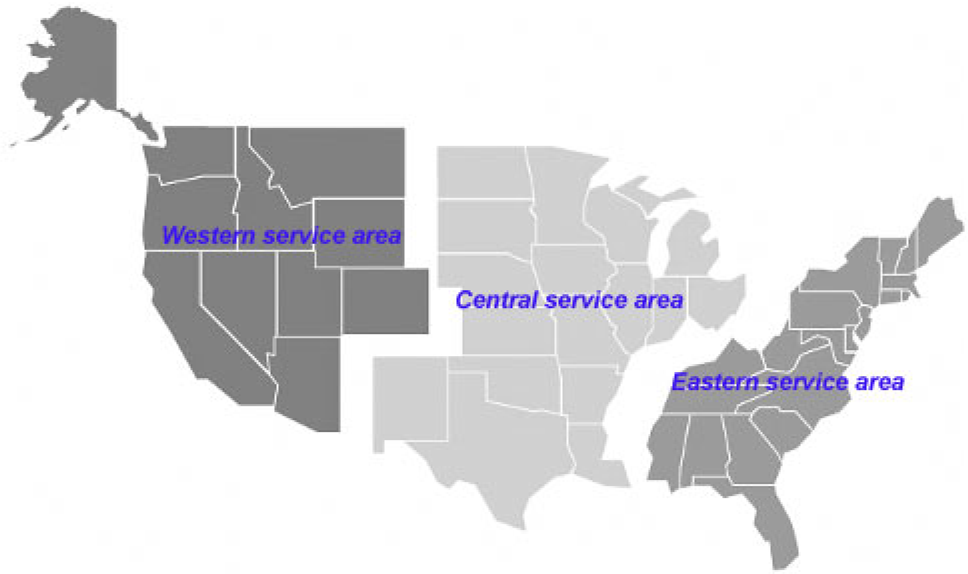

Figure 1.1 ADS-B Coverage Map [1]

In ADS-B system, the aircraft broadcast once per second to Air Traffic Control Stations and nearby aircraft. The broadcast information includes latitude and longitude, aircraft velocity, aircraft altitude, transponder code, aircraft's call sign, etc.

The ADS-B system also has data link capability that information can be transferred from the ground stations to aircraft during flight. Weather information is available as well as airspace status information by this type of data link.

ADS-B has the potential to increase capacity, improve management efficiency, reduce cost and environmental effect, and improve safety in the NAS. Applications not possible with today's radar technology can be performed with ADS-B service. Besides excellent air-to-air surveillance capability, ADS-B provides surveillance to remote or inhospitable areas that have not been currently covered with radar. It also provides real-time traffic and airspace information to pilots which can be shown on the cockpit display. Since

ADS-B can achieve a higher accuracy compared to traditional radar, it allows for reduced separation distance and greater predictability in departure and arrival times as well as collision avoidance which is a very important consideration of safety in ATC. It improves the ability of air traffic controllers to plan arrivals and departures in advance which leads to an increase in air traffic capacity. Also, ADS-B is helpful to reduce the cost of required infrastructure to operate surveillance system since ADS-B is a GPS based technology is the U.S. and GPS instruments are common and not expensive relatively.

The improvement in safety, capacity, and efficiency as a result of moving to a GNSS-based navigation system will enable the Federal Aviation Administration (FAA) to meet the expected rapidly growth in air traffic in coming decades. Because ADS-B is a flexible and expandable platform, it can change and grow with the evolving aviation system.

The information transmitted from aircraft via ADS-B is dependent on the aircraft's onboard navigation unit. In ADS-B system, the aircraft with the required equipment box onboard become an integral part of the surveillance infrastructure in National Airspace System (NAS). As a result, it is crucial to ensure that aircraft are equipped with the required instruments. However, most benefits are not obvious until all aircraft are equipped. There are three major strategies for achieving full equipage, but they may lead to some opposition from stakeholders [2].

To identify the main benefits of ADS-B, especially on technical side, a thorough understanding of ADS-B system and its advantages and disadvantages compared to traditional system is required. It also may be helpful to partially against the opposition and make decisions on ADS-B. To develop this kind of understanding is the basic motivation for this thesis.

CHAPTER 2. BACKGROUND AND HISTORY

2.1 Air Traffic Control

Air traffic control (ATC) is a service provided by ground-based controllers who direct aircraft on the ground and through controlled airspace, which can also provide advisory services to aircraft in non-controlled airspace. The primary purpose of ATC worldwide is to avoid collisions between aircraft, avoid collisions on maneuvering areas between aircraft and obstructions such as mountains and buildings on the ground, organize and expedite the flow of air traffic, and provide information and other support for pilots. [4] To prevent collisions, ATC develops traffic rules for separation service, which ensure each aircraft always maintains a minimum amount of empty space around it. There is usually also a collision avoidance system on aircraft, which provides additional safety by warning pilots when other aircraft get too close.

The National Air Space System uses zones to control air traffic. There are various types of control centers in these zones. The system is designed to keep aircraft separated safely and running smoothly from zone to zone.

Air Traffic Control System Command Center (ATCSCC) oversees the nationwide system. The U.S. airspace is divided into 22 zones called centers. An Air Route Traffic Control Center (ARTCC) is assigned to controls each center, except some smaller zones in which there are their own control centers. Terminal Radar Approach Control (TRACON) controls air traffic in a region with 80.5km diameter. Air traffic controllers can control arriving and departing flights within their regions which may include one or more airports. An air traffic control tower is located on every airport with regular scheduled air traffic. It handles traffic that is taking off, landing, or moving on the airfield. Controllers in the air traffic control tower direct air traffic in a region with about 8km in diameter. Terminal Radar Control is a separate facility from air traffic control tower locating in the base of the tower or at another airport nearby. For example, the Chicago TRACON is located in Eglin, IL, and it handles traffic for O'Hare, Midway and other Chicago-area airports.

2.2 ADS-B Technology

Air Traffic Control (ATC) was initially operated via aircraft position reports over radio to air traffic controllers in order to separate aircraft. In current air traffic control system in the US, ground based radar is used to determine position and velocity of aircraft. However, most modern aircraft have advanced navigation systems which perform better accuracy determination on aircraft's position and velocity rather than current radar system. For example, Traffic Collision Avoidance System (TCAS) works by one aircraft interrogating other aircraft' transponders. In this way, each TCAS equipped aircraft can locate nearby transponder equipped aircraft, and potential collisions can be detected. This is a semi-independent surveillance technology in that it does not require any ground infrastructure but it requires TCAS equipment or at least a Mode C transponder to send signals [2].

The next evolutionary step in aircraft surveillance technology is ADS-B. ADS-B broadcasts the more accurate information of aircraft and resulting in the potential to provide higher position and velocity accuracy, direct heading information as well as weather and airspace information. Also, ADS-B has a higher update rate which is once per second than radar which updates once every 4.8 seconds in the terminal area and only once every 12 seconds in en-route airspace [2]. Since ADS-B only uses relatively simple and low maintenance antennae as ground infrastructure, ground station can be located in more strategic locations, which may increase total surveillance coverage area and reduce environmental effect and cost.

The characteristics of ADS-B have been reflected from its name. The service is always on and operates without any operator intervention so that it is automatic. It depends on an accurate Global Navigation Satellites System (GNSS) signal for position data and other information and there is a requirement of equipment onboard as well. It provides a surveillance service like radar but it is more accurate as a replacement of SSR in the future. It continuously broadcasts aircraft position and other data to ground station and any aircraft in the area equipped to receive ADS-B.

ADS-B consists of two services, ADS-B Out and ADS-B In.

Through a transmitter onboard, ADS-B Out broadcasts information about each aircraft, such as aircraft identification, current position, altitude, and velocity periodically. It provides real-time position information which is usually more accurate than the information available with current radar-based system to air traffic controllers in ground stations as well as other equipped aircraft in the airspace. With these information, it will be able to position and separate aircraft in shorter time and shorter distance which leads to improvement in management efficiency.

ADS-B in does not require additional equipment, allowing participating aircraft to receive traffic and weather information from ADS-B ground stations and nearby aircraft broadcasting their positions through ADS-B Out. The information which can be received by ADS-B Out includes latitude and longitude of aircraft, aircraft altitude, aircraft velocity, transponder code, aircraft's call sign, weather information and airspace status information. This information can be displayed in the cockpit to improve situational awareness.

The system relies on two avionics components, a GPS navigation source to get navigation results and a datalink to communicate with ground stations and other aircraft.

The ADS-B avionic box onboard consists of four parts, GPS Receiver, Universal Access Transceiver (UAT) at 978 MHz, antenna and multi-function cockpit display capable of receiving and displaying broadcast service information as shown in Figure2.

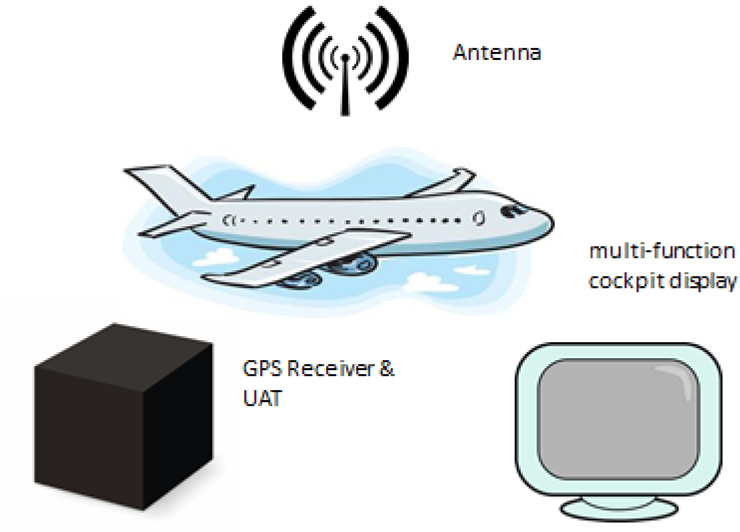

Figure 2.1 ADS-B Onboard Model

FAA has mandated that aircraft operating in airspace which now requires a Mode transponder must be equipped with ADS-B Out by Jan. 1, 2020. However, the ADS-B Out rule does not affect current transponder requirements, meaning aircraft must continue to carry their transponders even after equipping for ADS-B Out [5].

The following picture show the basic way of how ADS-B works.

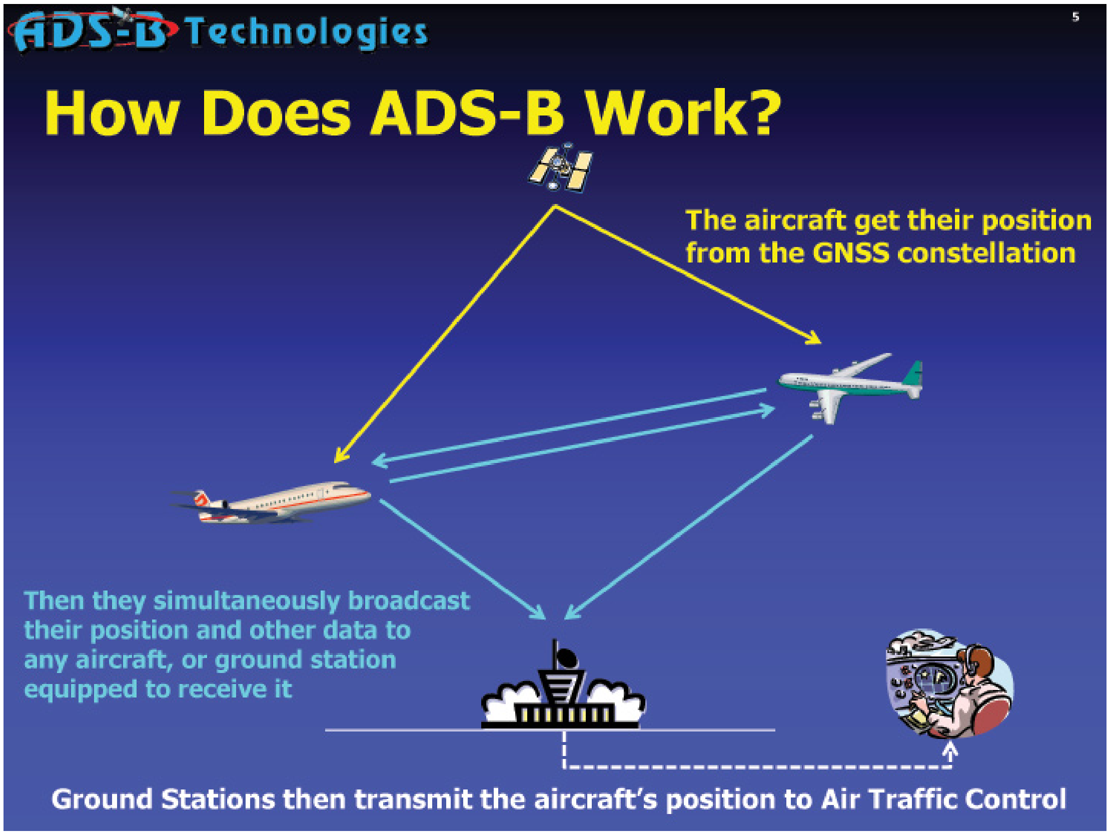

Figure 2.2 How Does ADS-B Work [3]

ADS-B uses conventional Global Navigation Satellite System (GNSS) technology and a relatively simple broadcast communications link as its fundamental components. The aircraft with ADS-B service uses an ordinary GNSS (GPS, Galileo, etc., GPS in the U.S.) receiver to derive its precise position from the GNSS constellation, and then combines that with other elements, such as speed, heading direction, altitude or information of nearby aircraft. This information is then broadcasted by transceivers onboard to other aircraft in ADS-B system and to ground air traffic control stations by transceivers onboard.

2.3 Radar Technology

Radar technology was developing during WWII and then air traffic controllers were able to obtain aircraft positions without radio reports. Primary surveillance radar (PSR) works by reflecting radio waves off of airframes. No equipment is needed on the aircraft, thus primary radar is an independent surveillance technology. However, it reflects off of other objects like birds, ground buildings and atmospheric phenomena, which makes it hard for controllers to identify aircraft uniquely. Primary radar has been enhanced with the Air Traffic Control Radar Beacon System (ATCRBS), which is more commonly known as secondary surveillance radar (SSR). In this system, each aircraft is equipped with a transponder which replies to interrogations from ground radars with unique data [2]. The air traffic control surveillance currently consists of two major systems which are primary surveillance radars and secondary surveillance radars.

The following picture shows the basic way of traditional radar’s work.

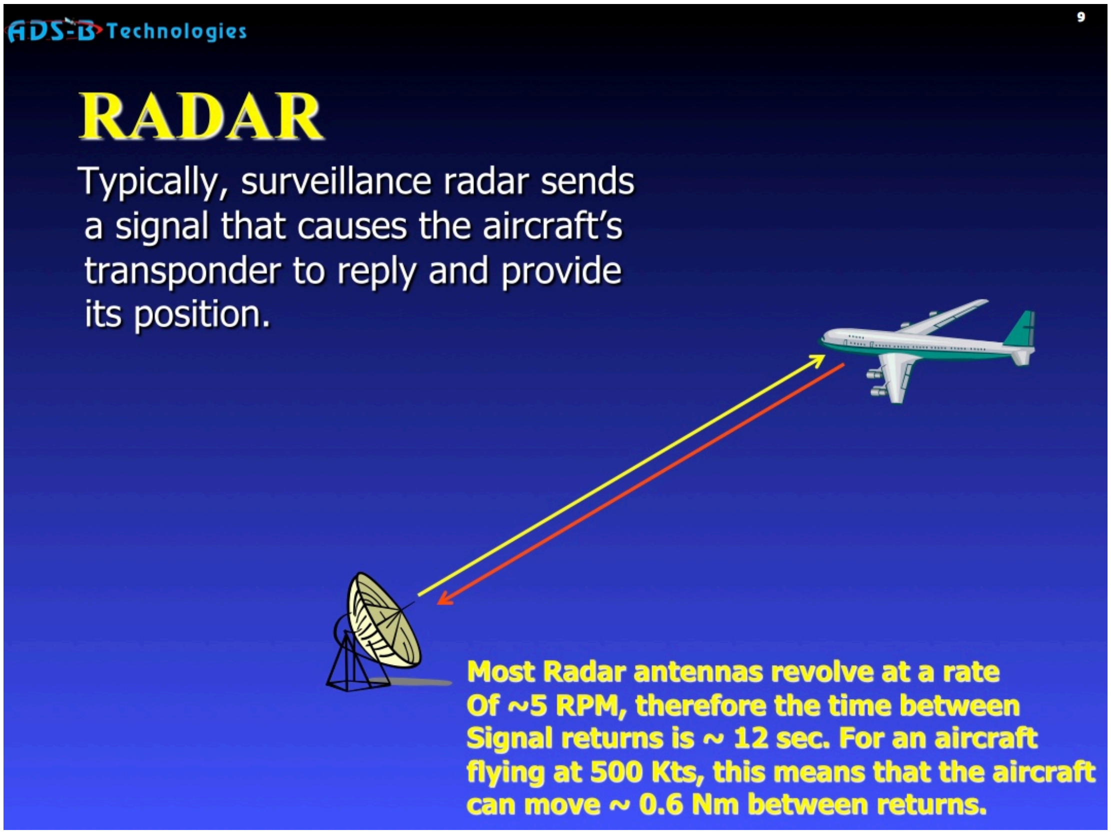

Figure 2.3 How Does Radar Work [3]

The radar works by bouncing radio waves from fixed terrestrial antennas off of airborne targets and then interpreting the reflected signals. The accuracy of radar navigation seriously changes with range, atmospheric conditions, or target altitude. The update intervals depend on the rotational speed or reliability of mechanical antennas. Generally speaking, the radar navigation updates aircraft's information about once per 4 to 12 seconds.

Primary radars use the electromagnetic waves reflection principle. The system measures the time difference between the emission of wave and the reception of the reflected wave on a target in order to determine the distance between the radar and the target.

The target position is determined by measuring the antenna azimuth at the time of the detection [6].

Since reflections occur on the targets as aircraft but also on fixed objects like buildings, mountains or mobile objects like cars, disturb the navigation of aircraft in air traffic control is disturbed by these detections.

Secondary surveillance radar (SSR) is a radar system that not only detects and measures the position of aircraft, but also requests additional information from the aircraft itself such as its identity and altitude. This is an improvement in air traffic surveillance from PSR since PSR cannot easily obtain altitude information. Unlike primary radar systems, SSR interrogates aircraft transponders which respond with aircraft information. As a result, aircraft must be equipped and respond to the interrogations in order for SSR to work. On the other hand, there is no requirement of onboard equipment in PSR system in order to be tracked.

Secondary Surveillance Radar system includes two elements: an interrogative ground station and a transponder on the aircraft. The transponder answers to the ground station interrogations with its range and its azimuth.

Mode A/C and then Mode S appeared in the development of SSR for the civil aviation. Transponders in Mode A give the identification and Transponders in Mode C give the altitude of the aircraft so that the ground station knows the 3-dimension position and the identity of the targeted aircraft.

Mode S is an improvement of the Mode A/C as it contains all its functions and allows a selective interrogation of the targets because it uses a unique address coded on 24 bits as well as a bi-directional data link allowing the exchange of information between air and ground [6].

The radar system in air traffic surveillance can be further divided into en-route and terminal radars. En-route radars have a slower update rate which is about 12 seconds in standard. However, it covers a much larger geographic area. Terminal radars have a faster update rate about 4.2 seconds for terminal operations near airports, while covering a smaller geographic area [2]. The entire continental US is covered by radar at high altitudes (24000 feet), but the radar coverage varies at lower altitude. Figure 2.4 shows the radar coverage at low altitude in the continental US. As seen here, there are small gaps of low level radar coverage in the regions like Southeast, along the West Coast, and Northwest.

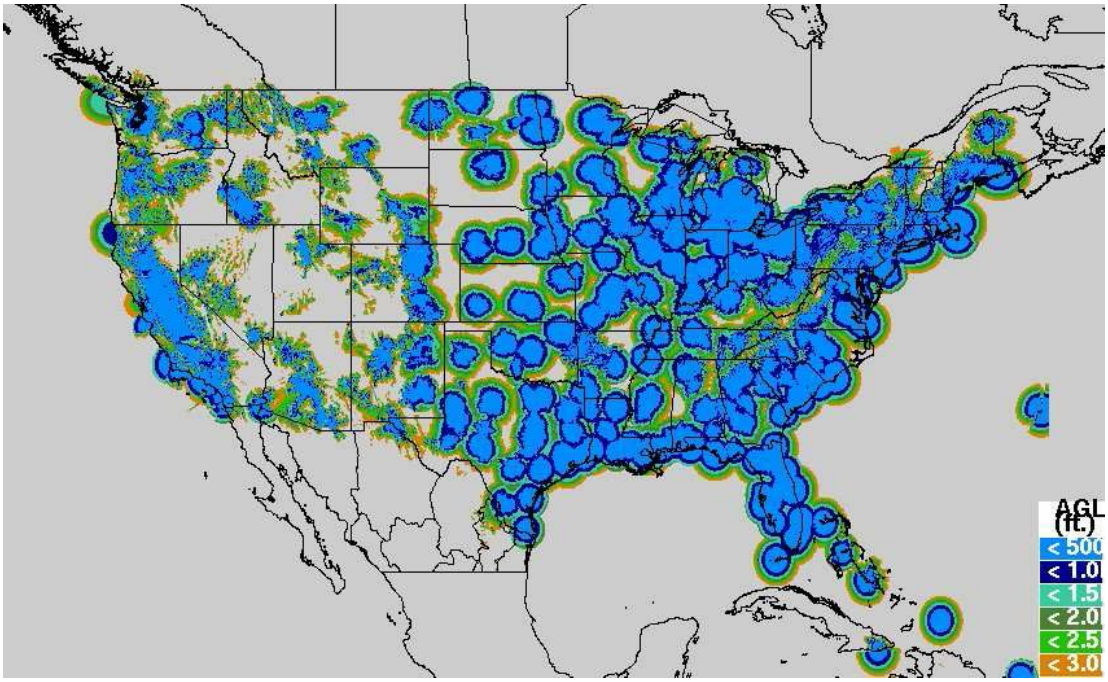

Figure 2.4 Radar Coverage at Low Altitude in Continental US [2]

CHAPTER 3. EXPERIMENT OF ACCURACY IN MATLAB

3.1 Design Method

This experiment was designed to show the approximate accuracy of ADS-B navigation by GPS and then the results would be used to be compared to traditional radar navigation. Dilution of Precision (DOP) was introduced to express the accuracy of GPS here. It is used to specify the additional multiplicative effect of navigation satellite geometry on positional measurement precision. There are several sub-measurements of DOP. HDOP, VDOP, PDOP, and TDOP are respectively Horizontal, Vertical, Position (3D), and Time Dilution of Precision. PDOP, HDOP and VDOP are measured in this experiment. Due to the relative geometry of visible satellites to a receiver, the accuracy of visible satellites in view of a receiver and the relative position of these satellites will determine the level of precision in each dimension of the receiver measurement (x, y, z and t).

The most important influence factor of DOP is the arrangement of navigation satellites. When visible navigation satellites are close together in the sky, the geometry is said to be weak and the DOP value is high, while when they are far apart, the geometry is strong and the DOP value is low. Generally speaking, a more distributed satellites arrangement leads to better DOP, meaning higher accuracy, and vice versa.

Another factor that can increase the effective DOP is obstruction such as nearby mountains or buildings. However, except the geometry of satellites, other factors were not considered in this experiment.

The positional history data of flights were derived from FACET [15] database which were based on current radar navigation and GPS satellites positions were derived from official IGS database. Since the data of GPS satellites position from IGS [16] were given for every 15 minutes, the DOP in the experiment was also calculated on the same interval.

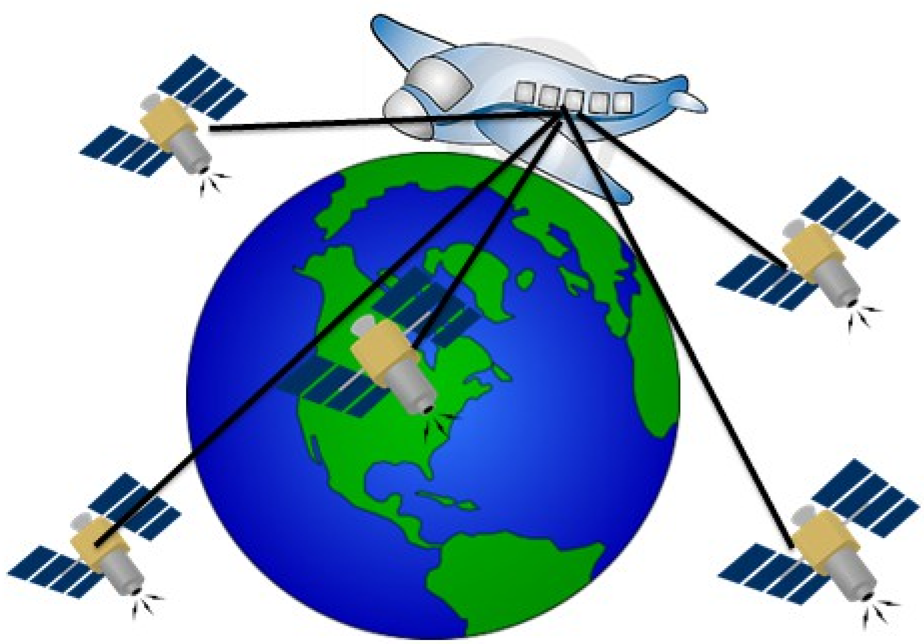

Figure 3.1 Satellite Navigation of Aircraft

Because the exact position of aircraft during flight cannot be known, the position derived from current radar navigation was assumed to be exact in this experiment.

3.2 Procedure

The DOP can be defined to express how errors in the measurement will affect the final state estimation as in Equation 3.1 [7].

$$\mathrm{DOP} = \frac{\Delta\text{Output Location}}{\Delta\text{Measured Data}} \qquad \text{Equation 3.1}$$

Ideally small changes in the measured data will not result in large changes in output location, indicating that the solution is very sensitive to errors.

Since the navigation satellites positional information is given every 15 minutes and the aircraft positional information is given every minute, linear interpolation in Equation 3.2 was used to find the position of aircraft at the point when GPS satellites positional information is given.

$$\mathrm{ACx} = (ACx_2 - ACx_1) * \frac{\mathrm{t} - t_1}{t_2 - t_1} + \mathrm{ACx}_1$$

$$\mathrm{ACy} = (ACy_2 - ACy_1) * \frac{\mathrm{t} - t_1}{t_2 - t_1} + \mathrm{ACy}_1$$

$$\mathrm{ACz} = (ACz_2 - ACz_1) * \frac{\mathrm{t} - t_1}{t_2 - t_1} + \mathrm{ACz}_1 \qquad \text{Equation 3.2}$$

Navigation satellites positional information was given in IGB08 frame in x, y, z dimensions and aircraft positional information was given in WGS84 ECEF frame with expression of longitude, latitude and height. Ignoring the slight difference between WGS84 and KGB08, same parameters were used in the calculation. Translation from longitude, latitude and height of aircraft to x, y, z expressions was done with Equation 3.3.

$$\mathrm{X} = (\mathrm{N} + \mathrm{H}) * \mathrm{cosB} * \mathrm{cosL}$$

$\mathrm{Y} = (\mathrm{N} + \mathrm{H}) * \cos\mathrm{B} * \sin\mathrm{L}$

$\mathrm{Z} = (\mathrm{N}(1 - \mathrm{e}^2) + \mathrm{H}) * \sin\mathrm{B}$ Equation 3.3

Where$\mathrm{N} = \frac{\mathrm{a}}{\sqrt{1-e^2*(\sin(B))^2}}$; $\mathrm{e} = \frac{\mathrm{a}^2-\mathrm{b}^2}{\mathrm{a}^2}$ which is the first eccentricity; a is the length of semimajor axis of ellipsoid which is 6378.137 km and b is the length of semiminor axis of ellipsoid which is 6356.7523141 km in this model. L represents longitude and B represents latitude.

Elevation angle decision in Equation 3.4 was made to determine which satellites are chosen during the experiment because in a view of the aircraft, only visible navigation satellites were considered to calculate DOP. The judgement condition in ideal situation was that when elevation angle of the satellite according to the aircraft was larger than zero, the satellite was visible from the GPS receiver onboard.

$$\text{elevation angle} = \arcsin\left(\frac{\mathrm{PG}_z - AC_z}{\sqrt{(\mathrm{PG}_x - AC_x)^2 + (\mathrm{PG}_y - AC_y)^2 + (\mathrm{PG}_z - AC_z)^2}}\right) \quad \text{Equation 3.4}$$

Where PG represents the position of one navigation satellite and AC is the position of the aircraft.

The minimum number of visible navigation satellites to determine the position of a receiver is 4. The distance between the satellite and the aircraft was considered as $R_i = \sqrt{(\mathrm{PG}_{x,i} - AC_x)^2 + (\mathrm{PG}_{y,i} - AC_y)^2 + (\mathrm{PG}_{z,i} - AC_z)^2}$, and the unit vector from the receiver to satellite i is $\left(\frac{\mathrm{PG}_{x,i}-AC_x}{R_i}, \frac{\mathrm{PG}_{y,i}-AC_y}{R_i}, \frac{\mathrm{PG}_{z,i}-AC_z}{R_i}\right)$. i can be any integer between 1 and 32 which represents the GPS navigation satellite.

According to a GPS textbook by Misra and Enge [8], to derive DOP, matrix A should be formulated as in Equation 3.5 first. This is an n by 4 matrix, where n is the amount of visible satellites according to the aircraft. n should be between 4 to 32, since 4 is the minimum number of visible satellites in a view of the receiver to be navigated by GPS and 32 is the maximum number of GPS navigation satellites.

$$A = \begin{pmatrix} \frac{\mathrm{PG}_{x,1}-AC_x}{R_1} & \frac{\mathrm{PG}_{y,1}-AC_y}{R_1} & \frac{\mathrm{PG}_{z,1}-AC_z}{R_1} & -1 \\ \frac{\mathrm{PG}_{x,2}-AC_x}{R_2} & \frac{\mathrm{PG}_{y,2}-AC_y}{R_2} & \frac{\mathrm{PG}_{z,2}-AC_z}{R_2} & -1 \\ \frac{\mathrm{PG}_{x,3}-AC_x}{R_3} & \frac{\mathrm{PG}_{y,3}-AC_y}{R_3} & \frac{\mathrm{PG}_{z,3}-AC_z}{R_3} & -1 \\ & \ddots & & \\ \frac{\mathrm{PG}_{x,n}-AC_x}{R_n} & \frac{\mathrm{PG}_{y,n}-AC_y}{R_n} & \frac{\mathrm{PG}_{z,n}-AC_z}{R_n} & -1 \end{pmatrix} \qquad \text{Equation 3.5}$$

The first three elements of each row of A are the components of a unit vector from the receiver to the indicated satellite.

Then matrix Q can be derived as in Equation 3.6, which is always a 4 by 4 matrix.

$$Q = (A^T A^{-1}) = \begin{pmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} & \sigma_{xt} \\ \sigma_{xy} & \sigma_y^2 & \sigma_{yz} & \sigma_{yt} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z^2 & \sigma_{zt} \\ \sigma_{xt} & \sigma_{yt} & \sigma_{zt} & \sigma_t^2 \end{pmatrix} \qquad \text{Equation 3.6}$$

Based on Q matrix, Position DOP, Horizontal DOP and Vertical DOP can be calculated as below.

$$\mathrm{PDOP} = \sqrt{\left(\sigma_x^2 + \sigma_y^2 + \sigma_z^2\right)} = \sqrt{HDOP^2 + VDOP^2}$$

$$\mathrm{HDOP} = \sqrt{\left(\sigma_x^2 + \sigma_y^2\right)}$$

$$VDOP = \sqrt{(\sigma_z^2)} \qquad \text{Equation 3.7}$$

Totally 57 sets of data were handled in this experiment. The results will be shown in next part 3.3.

3.3 Result

The data used in the experiment was based on flight history data of April.10, 2013. Four flights were chosen which are UAL1735, AAL505, AAL1062 and DAL2123.

The results of DOP and number of visible navigation satellites according to the aircraft are shown by column plots and line plots separately. The data details are also recorded in the tables below.

UAL1735 on April.10, 2013 was a flight from Los Angeles International Airport to Newark Liberty International Airport. The flight distance was about 3988 kilometers and duration was about 298 minutes.

Figure 3.2 Approximate Route for UAL1735 [9]

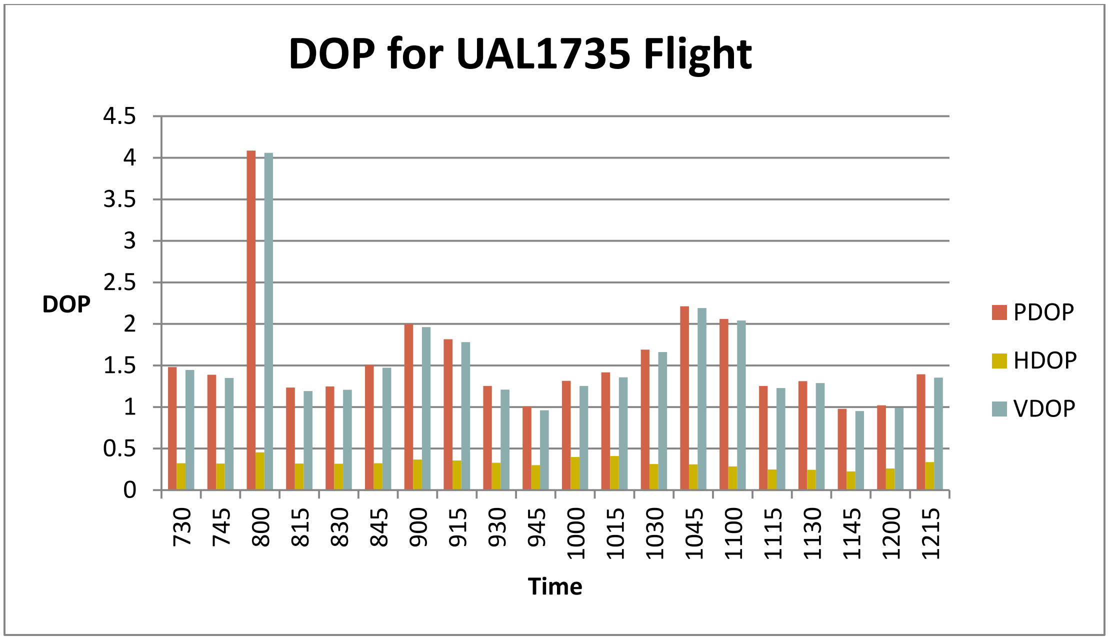

Figure 3.3 DOP for UAL1735

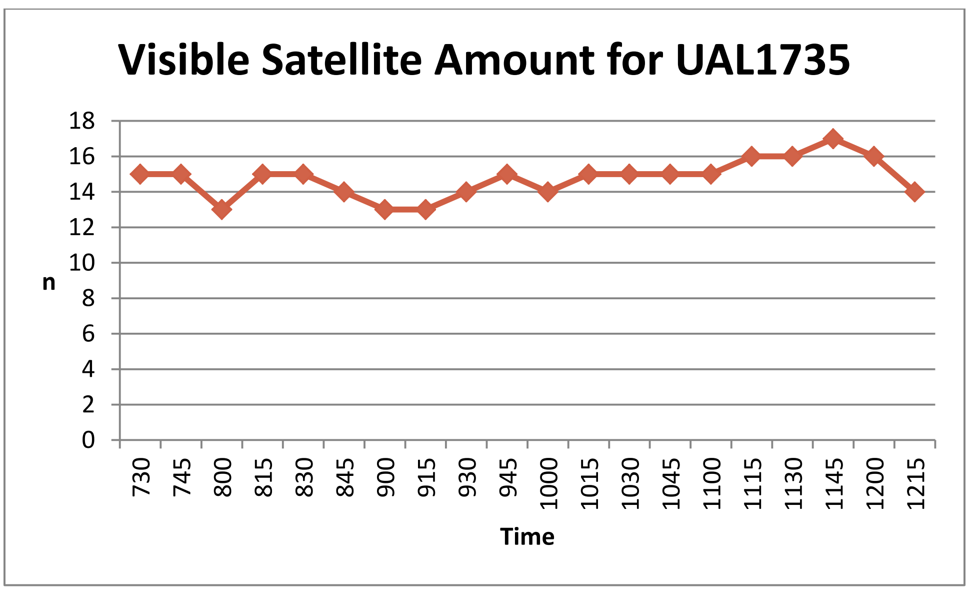

Figure 3.4 Visible Satellite Amount for UAL1735

Table 3.1 DOP and Visible Satellites for UAL1735

average PDOP	1.583484
average HDOP	0.321892
average VDOP	1.547619
average n	14.75

AAL505 on April.10, 2013 was a flight from Logan International Airport (Boston) to Miami International Airport. The flight distance was about 2356 kilometers and duration was about 154 minutes.

Figure 3.5 Approximate Route for AAL505 [9]

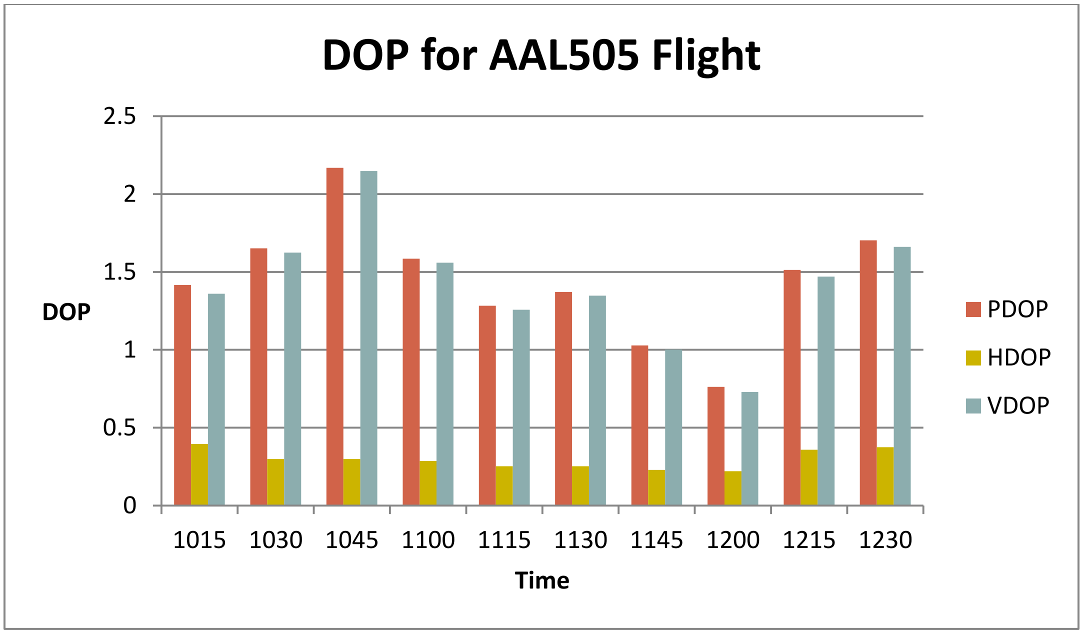

Figure 3.6 DOP for AAL505

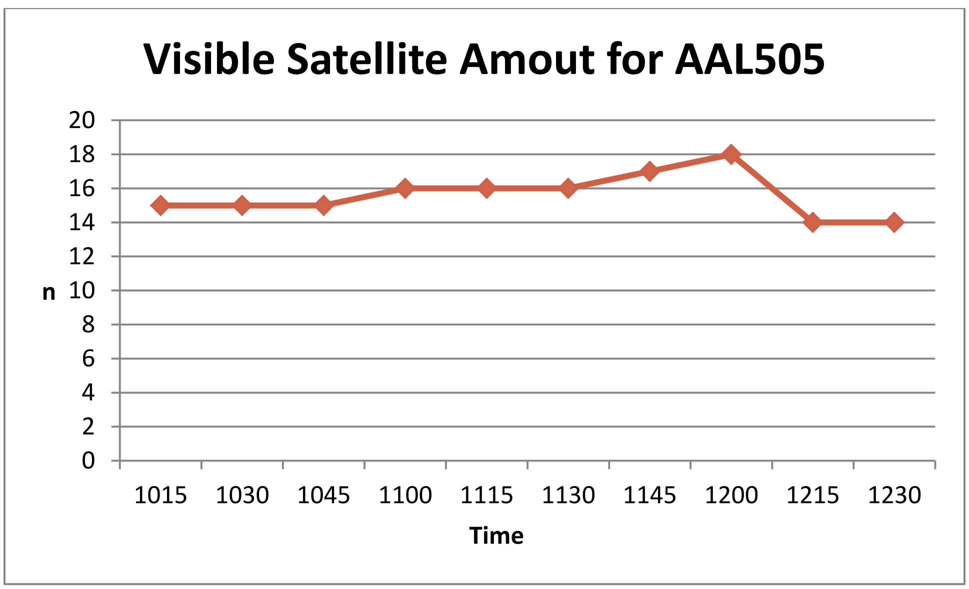

Figure 3.7 Visible Satellite Amount for AAL505

Table 3.2 DOP and Visible Satellites for AAL505

average PDOP	1.448076
average HDOP	0.296883
average VDOP	1.415816
average n	15.6

AAL1062 on April.10, 2013 was a flight from Los Angeles International Airport to Chicago O'Hare International Airport. The flight distance was about 3045 kilometers and duration was about 218 minutes.

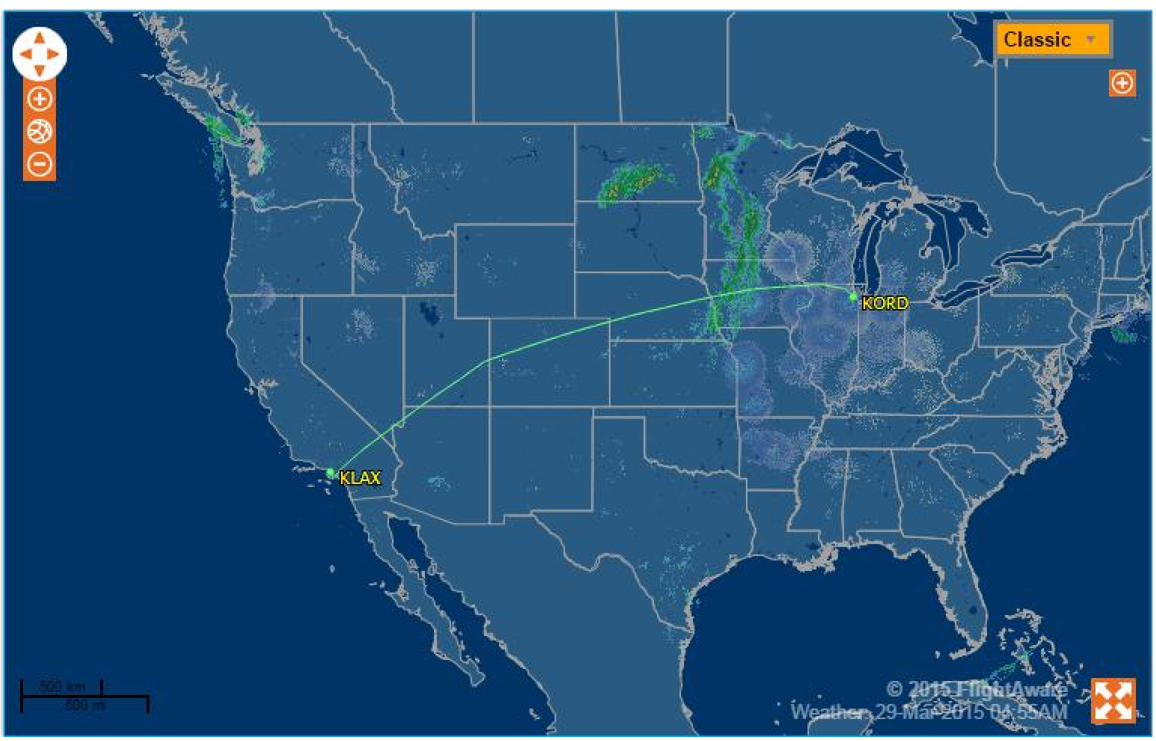

Figure 3.8 Approximate Route for AAL1062 [9]

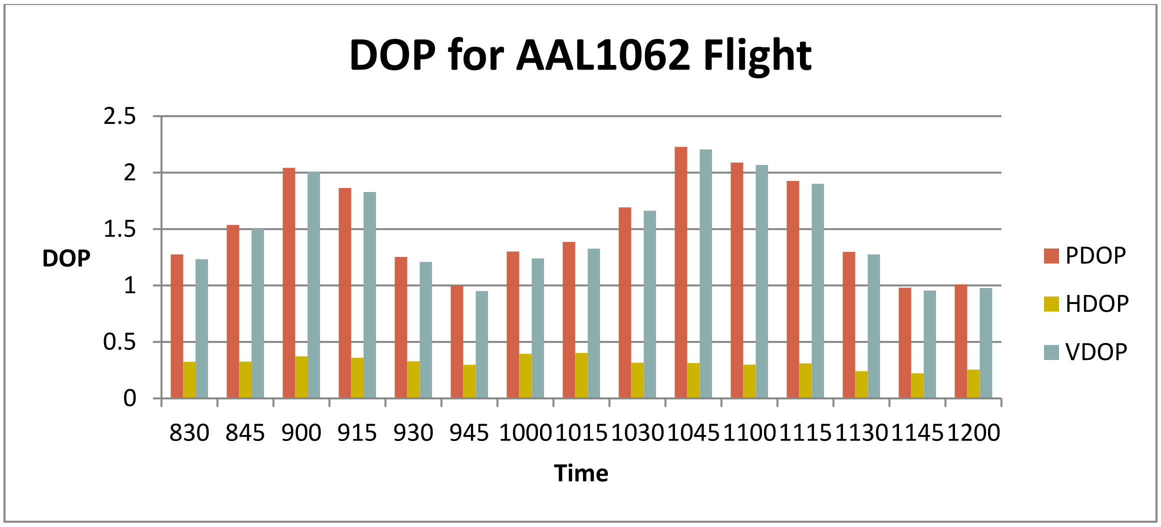

Figure 3.9 DOP for AAL1062

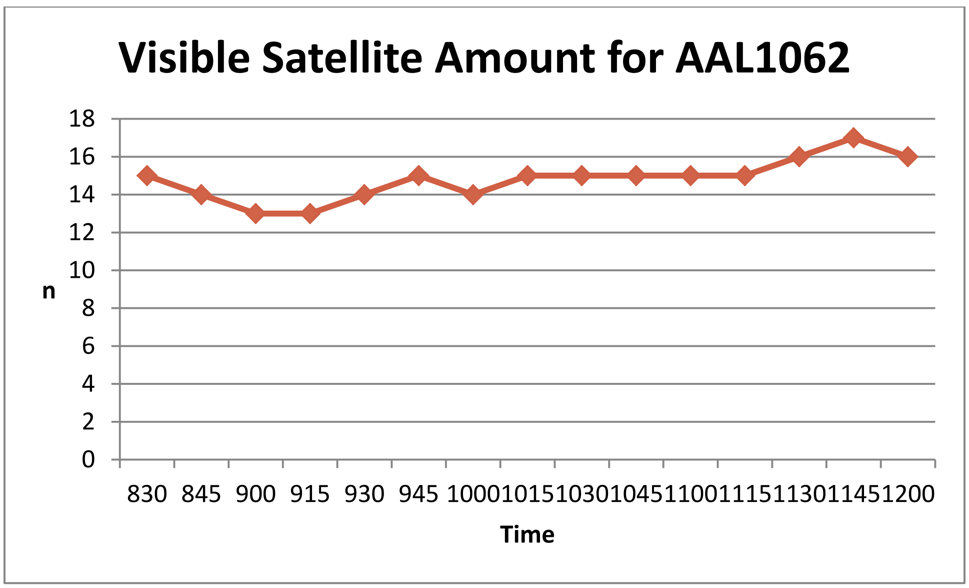

Figure 3.10 Visible Satellite Amount for AAL1062

Table 3.3 DOP and Visible Satellites for AAL1062

average PDOP	1.52545
average HDOP	0.317749
average VDOP	1.489675
average n	14.8

DAL2123 on April.10, 2013 was a flight from Phoenix Sky Harbor International Airport to John F. Kennedy International Airport. The total flight distance was about 3587 kilometers but here only part of the journey was used due to record limit. The duration used in experiment was about 180 minutes.

Figure 3.11 Approximate Route for DAL2123 [9]

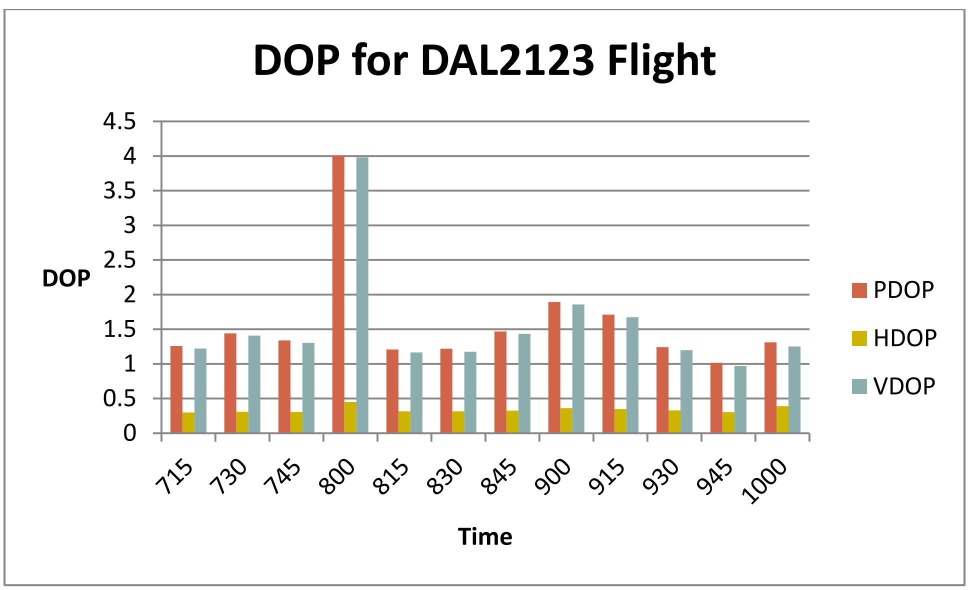

Figure 3.12 DOP for DAL2123

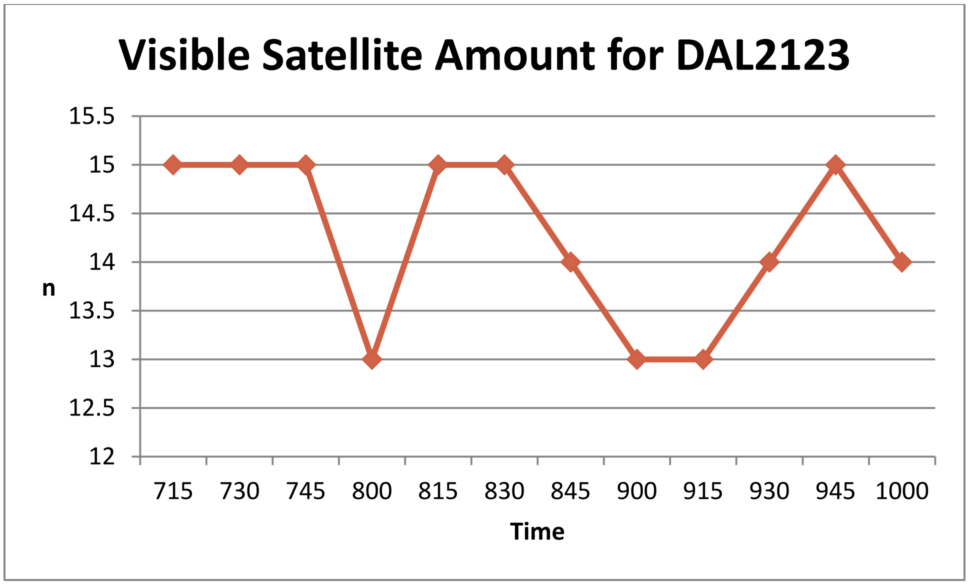

Figure 3.13 Visible Satellite Amount for DAL2123

Table 3.4 DOP and Visible Satellites for DAL2123

average PDOP	1.59243
average HDOP	0.337549
average VDOP	1.553193
average n	14.25

With all 57 sets of data, the average DOP and the amount of visible satellites are recorded in Table 3.5.

Table 3.5 Statistic Summary of DOP and Visible Satellites for All Data Sets

average PDOP	1.53736	Max PDOP	4.085831	Min PDOP	0.7617	STD PDOP	0.5945
average HDOP	0.318518	Max HDOP	0.454784	Min HDOP	0.221138	STD HDOP	0.0542
average VDOP	1.501576	Max VDOP	4.060441	Min VDOP	0.728893	STD VDOP	0.5985
average n	14.85	Max n	18	Min n	13		

3.4 Analysis

Generally, the result is ideal when the value of DOP is less than 1 which is highest possible confidence level to be used for applications demanding the highest possible precision at all times. When DOP is between 1 and 2, positional measurements are considered accurate enough on this excellent level. 2-5 is good on which level positional measurements could be used to make reliable in-route navigation suggestions to the user. 5 to 10 is moderate and 10 to 20 is fair which represents a low confidence level. Positional measurements could be used only to indicate a very rough estimate of the current location. When DOP is larger than 20, the accuracy is very poor. [10]

The final output errors of GPS navigation depend on DOP and measurement errors. Two sources of error are discussed here to derive measurement errors. The first one is receiver noise, which essentially smudges the signal, affecting precision of the code or carrier phase measurement. The code and carrier measurement are affected by random measurement noise, called receiver noise, which is a broad term covering the RF radiation sensed by the antenna, amplifiers, cables, and the receiver; multi-access noise; and signal quantization noise. The Multipath is the second one which introduces interfering signals changing the measured phase actually. It refers to the phenomenon of a signal reaching an antenna via two or more paths. Typically, an antenna receives the direct signal and one or more of its reflections. A reflected signal is a delayed and usually weaker version of the direct signal. The range measurement error due to multipath depends on the strength of the reflected signal and the delay between the direct and reflected signals. Multipath affects both code and carrier measurements, but the magnitudes of the error are different significantly. [11]

The measurement errors due to receiver noise and multipath depend on the satellite elevation angle in real situation. As a satellite gets lower in the sky, the received signal power decreases and multi-path increases. In this experiment, detailed effect is not considered to simply the procedure. A typical Measurement Error Model from Pratap Misra and Per Enge is adopted in this experiment as a general estimation [11]. These RMS errors for code and carrier phase measurements in this model are shown in Table 3.6.

Table 3.6 Typical receiver-related measurement errors (rms) in code and carrier phase measurements [11]

	Receiver Noise	Receiver Noise and Multipath (RNM)
Code phase	0.25-0.50 m	0.5-1.0 m
Carrier phase	0.005-0.01 cycle≈1-2 mm	0.025-0.05 cycle≈0.5-1 cm

In this model, the range error (RE) attributed to the Control Segment (CS) has an rms value of about 3 m. This number is based on empirical data. The rms residual range error due to atmospheric propagation models at mid-latitudes is about 5 m. The ionospheric component of the propagation error can be highly variable depending on the measured location, elevation angle of satellite and state of the medium. The rms range error due to receiver noise and multipath (RNM) is assumed to be 1 m. The combined error is referred to as the user range error (URE). It is reasonable to model the errors due to the satellite clock and ephemeris, atmospheric propagation, multipath and receiver noise to be uncorrelated, and the URE can be defined as in Equation 3.8 [11].

$$\sigma_{URE} = \sqrt{\left(\sigma_{\frac{RE}{CS}}\right)^2 + \left(\sigma_{\frac{RE}{P}}\right)^2 + \left(\sigma_{\frac{RE}{RNM}}\right)^2} \approx 6\ m \qquad \text{Equation 3.8}$$

The summary of pseudorange measurement errors in this model is shown in Table 3.7. In the past, when SA was active, σ_{URE} is about 25 m.

Table 3.7 Typical pseudorange measurement errors for a single-frequency (L1) receiver [11]

Error Source	RMS Range Error (RE)
Satellite clock and ephemeris parameters	$\sigma_{\frac{RE}{CS}} \approx 3\,m$
Atmospheric propagation modeling	$\sigma_{\frac{RE}{P}} \approx 5\,m$
Receiver noise and multipath	$\sigma_{\frac{RE}{RNM}} \approx 1\,m$
User range error (URE)	$\sigma_{URE} \approx 6\,m$

The statistic data of DOP for all 57 data sets are shown below. Figure 3.14, 3.15 and 3.16 show the histogram and normal distribution of PDOP, HDOP and VDOP.

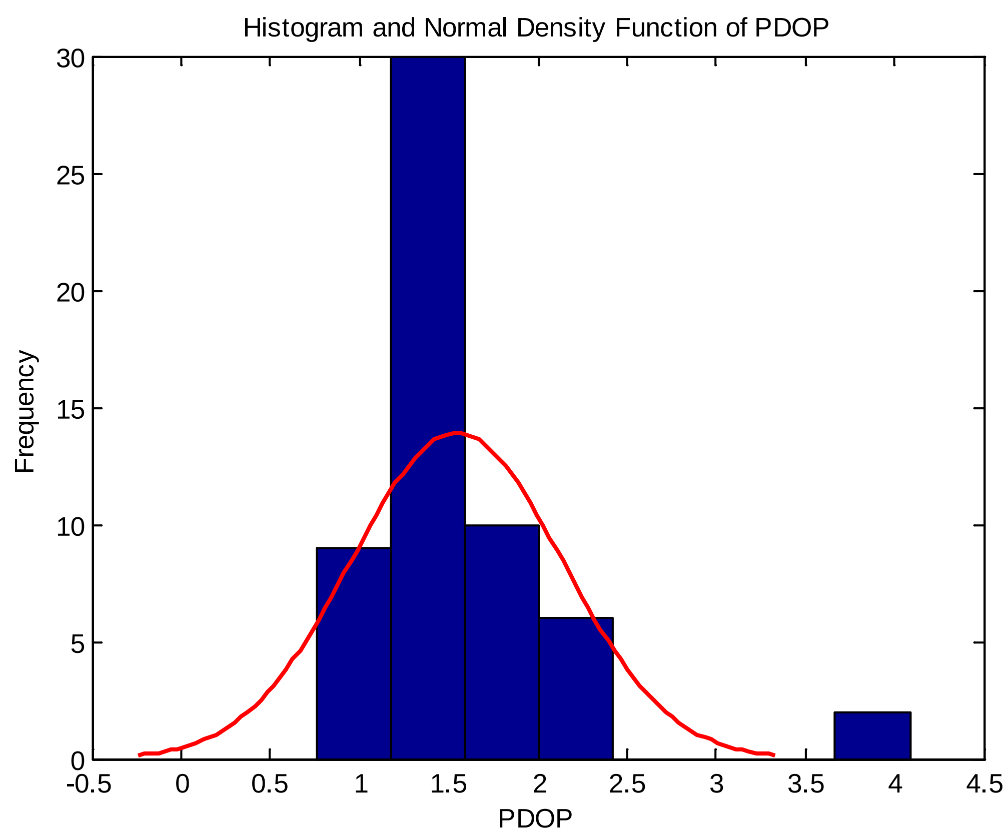

Figure 3.14 Histogram and Normal Distribution of PDOP

As seen from above graph, most data of PDOP fall around 1.5 and the average of PDOP is 1.59. According to Equation 3.1, the estimated output location error can be calculated as Position Output Location error=PDOP*Measured Data Error=1.59*6=9.54 m

The maximum PDOP among these data sets is 4.085830598 and the minimum is 0.7617. Most of PDOPs are less than 1 or between 1 and 2 which are on ideal or excellent performance level.

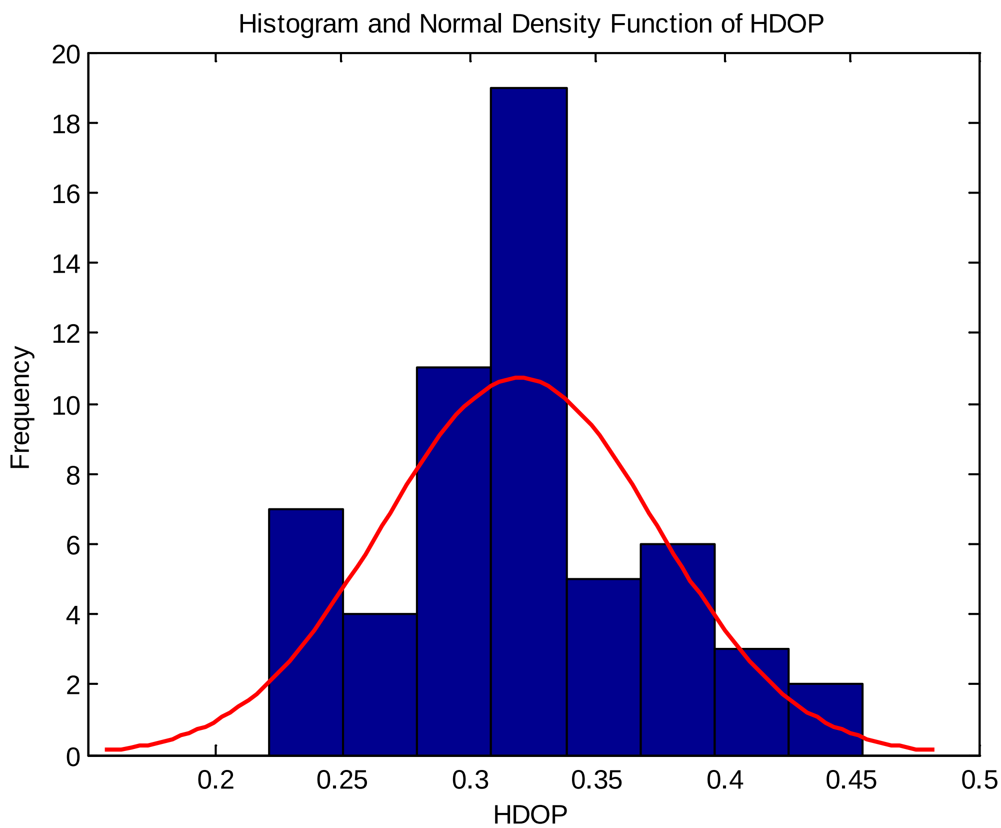

Figure 3.15 Histogram and Normal Distribution of HDOP

As seen from above graph, most data of VDOP fall around 0.3 and the average of HDOP is 0.32. According to Equation 3.1, the estimated output location error can be calculated as Horizontal Output Location error=HDOP*Measured Data Error=0.32*6=1.92 m

The maximum HDOP among these data sets is 0.454784453and the minimum is 0.221138371. All HDOPs are less than 1 which is on ideal level.

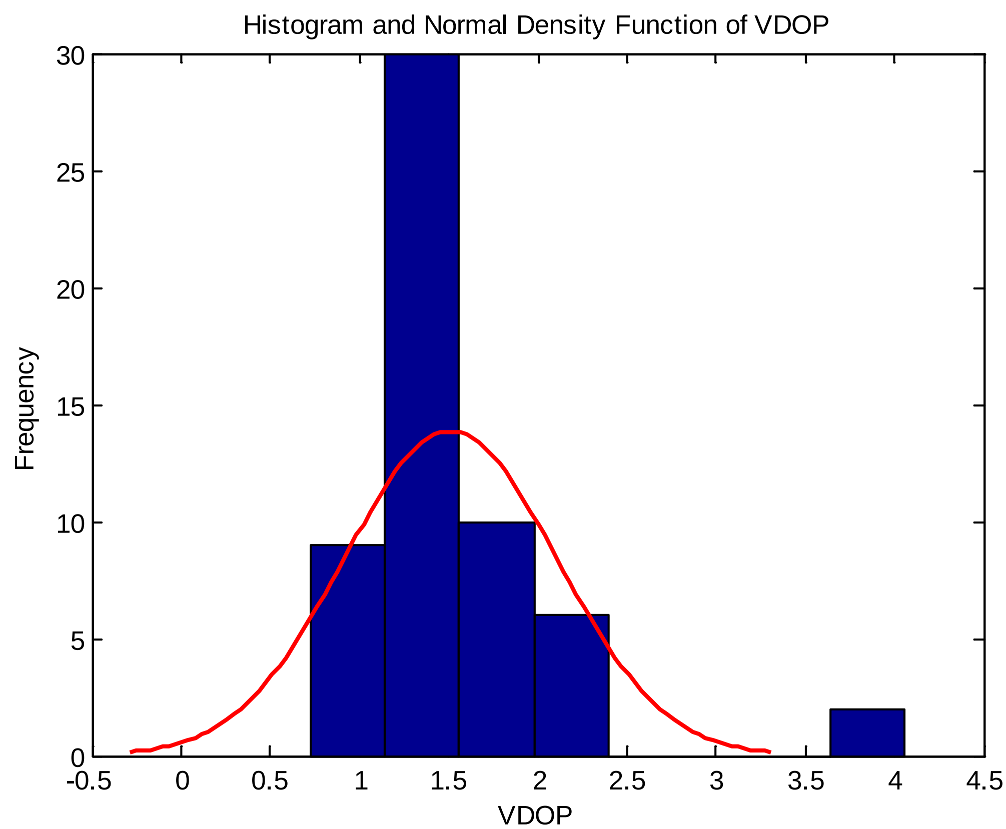

Figure 3.16 Histogram and Normal Distribution of VDOP

As seen from above graph, most data of VDOP fall around 1.5 and the average of VDOP is 1.50. According to Equation 3.1, the estimated output location error can be calculated as Vertical Output Location error=VDOP*Measured Data Error=1.50*6=9.0 m

The maximum VDOP among these data sets is 4.060441204 and the minimum is 0.728893092. Most of VDOPs are less than 1 or between 1 and 2 which are on ideal or excellent performance level.

From the distribution, the data point at 8 o'clock where PDOP and VDOP is about 4 for UAL1735 and DAL2123 is far from others. It may be an unreasonable data point due to several possible reasons which will be discussed in Section 3.5.

The performance levels of PDOP, HDOP and VDOP vary as expected. GPS is not accurate to determine altitude, as well as second radar surveillance system, so that vertical DOP is high compared to horizontal DOP. PDOP is a 3-D consideration of precision which is related to both HDOP and VDOP as seen in Equation 3.7, so when VDOP is high, PDOP is also high.

The visible satellite amount is around 13 to 18 which is good to satisfy the requirement that at least 4 navigation satellites should be visible in a view of the receiver to determine the position. Generally speaking, more visible satellites usually lead to a better accuracy of navigation.

3.5 Error Analysis

There are several sources of errors including systematic errors and random errors.

The first and most important one is that the exact location of aircraft is not known anyway. The basic idea is to compare the navigation accuracy of SSR and ADS-B at the same moment for the same aircraft. It requires the "true value" of aircraft position, and then the differences between measurements by different methods and true values can be compared. However, it is impossible to know the exact position of aircraft currently and in the past. All history data are based on current navigation system which is usually SSR. As a result, there is a combined effect of SSR navigation errors and ADS-B navigation errors on the results in this experiment.

The errors also may occur in original data. For example, the point of 8 o'clock is far from others. There may be something wrong in original flight history data or GPS satellites data. The altitude record is not accurate in nature since SSR is weak at determining altitude, as well as GPS.

One considerable factor is the limit of sample size. Less than 60 samples are used in this experiment. Even though the results are relatively good, if the sample size is much larger than current one, the statistic results will be more obvious and meaningful. Only time slots are available in this experiment. However, actually continuous orbits of satellites can be derived by some basic GPS orbit interpolation strategies like Lagrange's interpolation method. The flight path of aircraft can be determined more preciously if the velocity in history data is accurate. A continuous function of DOP will show more obvious and useful results to discuss the navigation accuracy of ADS-B system.

The number of visible navigation satellites in a view of receiver onboard is also not accurate. In real world, there are obstacles like mountains and huge buildings which restrict the range of visibility from the aircraft to satellites. But in the experiment, the only criteria to judge if a satellite is visible is elevation angle, meaning barriers were ignored in this ideal model. In a word, the amount of visible satellites may be less than that in this experiment and DOP may be higher than current results. There are other effects of signal propagation as reflection, delay, but they are not discussed in details too.

The differences between two reference frames are not considered in this case. IGS provided GPS satellites orbit data in IGB 08 reference frame since October 7, 2012 thru present. This frame is aligned to conventional ITRF2008 datum. The World Geodetic System (WGS) is a standard for use in cartography, geodesy, and navigation. The latest revision is WGS 84, established in 1984 and last revised in 2004. Flight history data were recorded using WGS 84 reference coordinate system and WGS 84 is also used by the Global Positioning System. There are some small changes of parameters between different versions of these reference frames. Since the difference in the result is just on the order of cm or mm magnitude, it is neglected in the experiment. However, expressions in different versions of reference frames can be transferred based on official guide.

Time DOP is not considered in this case since there are not relative data of radar navigation to compare with. Geometric dilution of precision (GDOP) is computed with Time DOP and Position DOP, which may lead to a better understanding of GPS navigation accuracy.

User range error estimation is also an important source of errors. Code phase measurement error can be modeled as a function of elevation angle. Generally speaking, as elevation angle increases, the pseudorange error decreases since the received signal power increases and multi-path decreases. The range of RMS pseudorange measurement error with combined effect is about 0.5-2 m. To simply the problem, the user range error is estimated as a fix value in calculation and not considered as a variable in the model.

The accuracy of radar navigation varies significantly among different types of radar instruments. Here only three samples are adopted to compare with ADS-B model. Both sensor error source and transponder error source are considered for radar. As a result, these results are not appropriate for every radar system in air traffic control.

3.6 Conclusion

The ideal model of ADS-B navigation has been successfully built in MATLAB to derive DOP at certain moments for commercial aircraft based on flight history data. The model performed well on most of these 57 data sets. According to DOP standard, all horizontal DOPs are on ideal level and most vertical and position DOPs are on excellent or good level. This result is as expected since both radar and GPS are good at navigating objects in horizontal dimensions but weak on measuring altitude. Except the points far from distribution, PDOP, HDOP and VDOP values are reasonable. The requirement of navigation is met and the expectation is satisfied by performance of HDOP which led to the success of this ideal model. Several sources of errors are also discussed and improvement is possible in future experiment. The current results are helpful in comparison with radar navigation and establishing a better understanding of ADS-B performance. More data and more detailed estimation can lead to a better result.

CHAPTER 4. COMPARISON OF ADS-B AND OTHER SURVEILLANCE METHODS

Nowadays, the radar is no longer the only technology able to provide the surveillance of air traffic. The development of satellite navigation systems and air-to-ground data links lead to the possibilities of other means and techniques to be adopted in improvement of air traffic surveillance.

ADS-B is a central component of the NextGen air traffic control modernization program. The service is intended to improve air traffic surveillance service by sharing accurate aircraft position information not only between pilot and air traffic controller but also between pilots. In addition, ADS- B provides pilots with nearby traffic information, as well as weather and airspace information.

In order to receive these services, aircraft must have appropriate onboard equipment including GPS receiver, Universal access transceiver (UAT) and multi-function cockpit display.

The U.S. Federal Aviation Administration (FAA) said the new GPS system will be much more accurate than radar. With the current air traffic surveillance system, controllers cannot see a plane flying over an ocean on radar until it is within about 200 nautical miles of land. Controllers often have to estimate a plane's location based on flight plans and departure times. [12] It is dangerous for planes if they have to land in an emergency.

The basic comparison between current radar system and ADS-B system is based on four factors: accuracy, update frequency, coverage and economic efficiency.

Accuracy. GPS accuracy is a measure for how well the GPS receiver is able to match the position estimate to its true position. As opposed to integrity, GPS accuracy assumes that all satellites are healthy and that there are no anomalous errors present in the signal [13]. For the accuracy of ADS-B navigation, results from last experimental part are used here. There are several references discussing errors or accuracy of radar. Here two sources are referred to compare with the accuracy of ADS-B in the experiment. One is from official brochure of commercial air traffic control radar and the other one is from academic paper discussing Surveillance Accuracy Requirements in Support of Separation Services [14].

Table 4.1 Range Errors of Radar Navigation

Radar	MSSR(Mode-S) from Thompson's Paper	MSSR(Mode-S) from INDRA [17]	MSSR(Mode-S) from RAMET [18]
Range Errors	180 ft=54.864 m	95.14 ft=29 m	196.85 ft=60 m
Azimuth Errors	0.068 deg	0.101 deg	0.1 deg

Both sensor error source and transponder error source are considered in the case from Thompson's paper and the sum of them is treated as range errors. Azimuth error is not measured in the experiment for ADS-B, so here azimuth error of radar is shown as reference without any value in comparison. When talking about range errors of radar, both uniform errors and standard deviation are shown in original references. However, due to a limit of sample size, only average range error of ADS-B in the experiment is considered to be compared.

Table 4.2 Range Errors of ADS-B Navigation

ADS-B	Horizontal	Vertical	Position (3-D)
Range Errors	1.92 m	9 m	9.54 m

New surveillance technologies such as ADS-B provide the potential to improve flight efficiency, increase airspace capacity, to reduce flight delays, etc. The improvement in surveillance accuracy may potentially reduce the minimum requirement of safe separation distance between aircraft. However, ADS-B may not fit with current radar-separation standards, because they assume that only radar technology provide the surveillance service. Table 4.3 shows the result from Thompson and Flavin's research, which tested the required surveillance accuracy to safely support separation between aircraft in NAS.

Table 4.3 Required Surveillance Accuracy [14]

Accuracy in measured separation	Three-mile separation	Five-mile separation
Standard deviation	No greater than 0.16 mi	No greater than 0.8 mi
No more than 10% of the error distribution shall exceed	±0.28 mi	±1.4 mi
No more than 1% of the error distribution shall exceed	±0.49 mi	±2.4 mi

No more than 0.1% of the error distribution shall exceed	±0.65 mi	±3.3 mi
Geographical position accuracy	σ<0.20 mi	σ<1.0 mi
Latency	2.2 sec to display maximum	2.5 sec to display maximum
Update rate	4.8 sec maximum	12 sec maximum

From the results shown above, it is obvious that ADS-B navigation meets this standard well. The development of ADS-B in air traffic control not only expands the airspace capacity but also improves the safety.

The influence factors vary a lot for ADS-B and current radar system. Satellites arrangement and measurement errors including receiver noise and multipath have much influence on the accuracy of ADS-B. However, for radar, the accuracy mainly depends on range, atmospheric conditions, or target altitude. The update intervals of radar depend on rotational speed or reliability of mechanical antennas while ADS-B always updates once per second because of the update frequency of GPS.

Update Frequency. ADS-B has a much higher update frequency than current SSR system. Usually the update frequency of current radar system is different for en-route and near terminal area since the higher accuracy is required to guarantee safety when aircraft is taking off and landing. Table 4.4 shows the comparison of update frequency directly between current SSR system and ADS-B.

Table 4.4 Update Frequency of Radar and ADS-B

Update Frequency	Radar	ADS-B
En-route	Once per 12 seconds	Once per second
Terminal Operation Area	Once per 4.2 seconds	Once per second

The improvement of update frequency also leads to improvement in safety since the information of aircraft is delivered more rapidly and it may be helpful to reduce required 3 mile and 5 mile separation distance.

Coverage. The coverage area is another important factor in comparison of current system and ADS-B system. Figure 4.1 and Figure 4.2 show ATC surveillance coverage above mean sea level in the continental US based on IFR altitude tracks and predicted ADS-B coverage at full implementation from Lester's paper and Kunzi's paper.

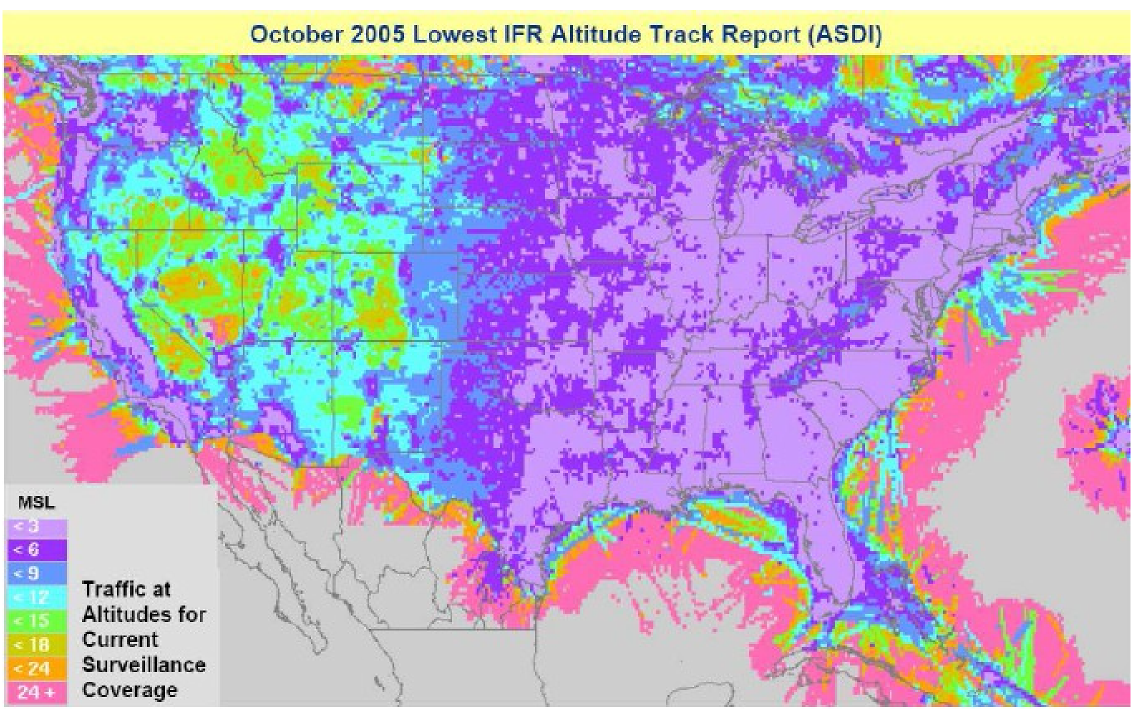

Figure 4.1 ATC Surveillance Coverage above Mean Sea Level in the Continental US based on IFR Altitude Tracks [2]

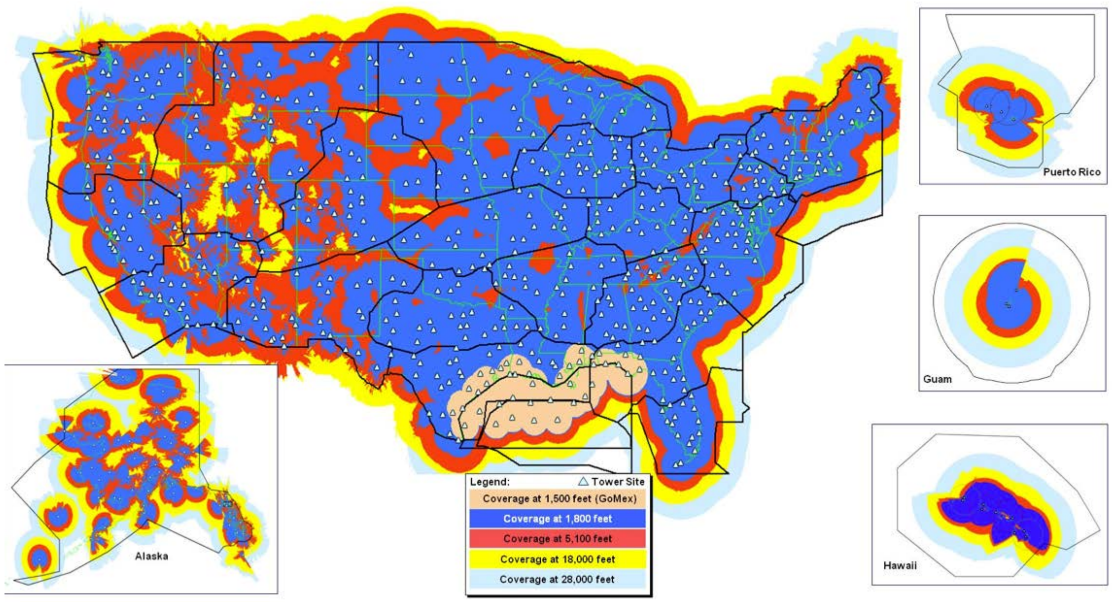

Figure 4.2 Predicted ADS-B Coverage at Full Implementation [13]

The entire continental US is covered by radar above 24000 feet. From these graphs, it is easy to see that at high altitude like over 18000 feet, both of the systems cover almost all continental US, while ADS-B has a better coverage at low attitude rather than current radar system. The better coverage leads to promptly delivery of airspace information. It may not be able to receive radar signal on time when flying over ocean or in any special area out of range, while ADS-B program can solve this problem due to the high coverage of GPS.

Economic efficiency. Economic factor is not a key in this discussion. As FAA recommended, ADS-B is high economic efficient since onboard equipment is common and no more ground infrastructure should be built new for that. However, the mandate equipment requirement still causes some opposition. The high cost of the necessary avionics and the lack of direct benefits are the two greatest barriers to the adoption of

ADS-B by a number of aviation operators. The current cost to install mandated ADS-B Out equipment is at least $5,000 to $6,000. For pilots and aviation operators, no new airspace is open by ADS-B service and it is hard to see any obvious and huge benefits. As a result of this high cost/low value equation, the FAA estimated that just 10 percent of the general aviation fleet was equipped for ADS-B Out at the end of the 2014 fiscal year [5]. This is the difficult circumstance FAA and ADS-B program meet now.

The adoption of current radar procedures outlined in FAA rules allows for the use of ADS-B and radar surveillance together. As a result, even though SSR may not be good as ADS-B in air traffic surveillance, it can still serve as a backup in air traffic control in case.

CHAPTER 5. SUMMARY AND CONCLUSION

Air traffic is expected to grow 2 to 3 times the current level by 2025. The increase of air traffic demand leads to a requirement of larger airspace capacity. ADS-B has the potential to satisfy the new requirement on capacity, accuracy and safety.

Automatic dependent surveillance – broadcast (ADS–B) is a central component of the NextGen program. This surveillance technology can replace current secondary surveillance radars (SSR) and enhance cockpit situational awareness. ADS-B broadcasts the more accurate aircraft position information not only between pilots and but also between pilots and air traffic controllers. In addition, ADS-B provides pilots with weather and airspace information as well as air traffic information for nearby area. In order to receive these traffic and weather services, aircraft must have appropriate onboard equipment including GPS receiver, Universal Access Transceiver, antenna and multi-function cockpit display. The most important potential of ADS-B is to provide high accurate navigation rather than current navigation system in air traffic control.

Compared to traditional surveillance technology used in air traffic control, aircraft with ADS-B service has a higher update frequency to broadcast its information. These features are useful in improvement of Reduced Vertical Separation Minimum (RVSM) and Traffic collision avoidance system (TCAS). ADS-B has a larger coverage as well including most of the area in the world. The feature is especially obvious at low attitude which offers a great opportunity for small size private aviation. It is also helpful in special areas such as mountain area, over ocean or any place out of 200 nm range for air traffic controllers. These features enable procedures not possible with current system that would increase the capacity of airspace system, guarantee more safety of flight and environmental effect. The cost of ADS-B operation seems low since it only uses relatively simple and low maintenance antennae as ground infrastructure, but total cost of the equipment onboard is still expensive for general aviation operators. The economic efficiency of ADS-B program is controversial. As a result, even though FAA highly recommended it and planned to require mandate adoption of ADS-B by 2020, the opposition from air operators exists for a long time.

The experiment focuses on the accuracy of ADS-B navigation compared to current radar system. GPS satellite data are got from IGS official website and history data of four flights on April.10 2013 from FACRT are used as samples. The model is built in MATLAB and DOP is calculated to derive range errors of ADS-B. The range errors of ADS-B in the experiment are less than range errors of chosen radars. Accuracy in horizontal dimension is better than in vertical dimension as expected. Experimental errors are within reasonable ranges and discussed after the experiment to make possible improvement in the future. The results show that ADS-B has a higher navigation performance in this ideal model and can meet the requirement of separation well.

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